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Research Article

Impact of Hypobaric Technology Combined with Fumigation on Freshness Preservation of Post-harvest Litchi

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Abstract: Litchi is rich in nutrients, which is quite beneficial for improving the physical quality of people, but litchi browns in a few days at room temperature, and the shelf life is very short. To study the influence of hypobaric storage on the storage quality of litchi after harvest, a hypobaric storage device combined with fumigation technology was used to fumigate litchi, and the change in pressure and temperature distribution in the hypobaric chamber was simulated. Secondly, during the hypobaric fumigation, litchi was divided into four groups with uniform quality, and humidified at 0%, 2%, 3%, and 5%, respectively. The temperature of the surface and center of the litchi was measured using a thermocouple. The research results show that in the simulation verification, the changes in pressure and temperature in the vacuum chamber during the experiment are basically consistent with the simulated values, and under different humidification specific gravity, when the humidification specific gravity is 3%, the center temperature and surface temperature drop the fastest, in which the surface temperature drops to 277.15 K, and the center temperature drops to 283.15 K, and the hypobaric fumigation and pre-cooling reaching the same temperature. The time required is also minimal.

***Keywords*:** hypobaric storage, fumigation, litchi, freshness keeping, weight loss ratio

1. Introduction

Litchi is an evergreen tree belonging to the Sapindaceae family. It is mainly distributed in the southwest, south, and southeast of China and has a long history of cultivation in China [1]. Litchi has a broad market prospect, with high cost, high input, and high yield, which can greatly promote economic development. At the same time, litchi is rich in high nutritional value, the flesh is translucent and greasy when fresh, and the taste is delicious. However, due to its maturity in the high-temperature season, the peel is prone to browning after picking, and the fruit easily loses water, so it is not tolerant to storage [2]. If it is not handled properly, it will cause huge decay and commercial value will be greatly reduced [3-5]. The reason for this is that China's cold chain circulation rate is low, and the cold chain transport efficiency is also low. Based on this, the country needs to strengthen the policy and financial support for litchi fruit farmers and establish a sound policy support system [6], aiming at promoting the healthy development of litchi industry and improve the efficiency and reliability of cold chain logistics.

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At present, the preservation technology of litchi at home and abroad mainly includes air conditioning preservation [7-10], coating preservation [11-14], chemical preservation [15-18], low-temperature preservation [19, 20], and so on. Under the condition of maintaining the physiological state of litchi, air conditioning preservation is usually used to reduce the concentration of oxygen and increase the concentration of carbon dioxide to inhibit the respiratory intensity of litchi and reduce the substance consumption in litchi, to delay the decay and aging of litchi, extend the storage period, and achieve the purpose of maintaining fresh and edible state for a longer time. However, the use of high-purity inert gas is relatively high cost [14]. Coating preservation can effectively reduce the respiration intensity of fruit and reduce the consumption and utilization of fruit's energy, but film treatment is difficult to completely cover, and the effect is not significant [16]. Chemical preservation uses chemical reagents for fumigation or soaking treatment to extend the freshness period, at room temperature can inhibit the growth of microorganisms, to achieve the purpose of long-term preservation, and has the advantages of low cost, less dosage, and simple and convenient operation [15]. However, the use of pharmaceutical fumigation methods such as fungicides for fumigation or soaking may leave residues on the surface or inside of litchi, which may affect human health if the residue exceeds the national standard. Low temperature storage effect is good [11], for fruit and vegetable products in the case of no freezing damage, the use of low temperature can effectively inhibit the respiration intensity of fresh fruit, and fresh fruit in a near dormant state delays the decay. The low-temperature state can be combined with a certain humidity environment, which can effectively reduce the water evaporation of fresh fruit and reduce the weight loss, but when the litchi stored at low temperature is transferred to the normal temperature shelf, the shelf life is short and the browning is fast.

As a new development of fresh-keeping technology, compared to the previous preservation technology, hypobaric fumigation storage can form a low-pressure and low-oxygen storage environment and extend the storage period of fruits and vegetables [21]. Hypobaric fumigation storage can also effectively slow down the respiratory intensity of fruits and vegetables, reduce the consumption of nutrients, and maintain freshness and nutritional value. Hypobaric fumigation storage process, up to 1 hour can inhibit 90% of the respiratory heat and 90% of ethylene production rate [5]. The exogenous ethylene was removed from the storage environment under reduced pressure in time. Also, eliminates field heat; Inhibits the infiltration of pathogenic bacteria; Kills insects; and maintains a high moisture content of items [22]. This is an important reason why hypobaric fumigation storage is obviously superior to other storage methods. Therefore, based on the above preservation status of litchi, this paper adopts hypobaric storage equipment to carry out experimental research on hypobaric fumigation storage of litchi, and better explore the changes in weight loss and temperature of litchi during the process of hypobaric fumigation storage.

2. Hypobaric fumigation storage and mechanism of litchi

Litchi is not sensitive to low temperatures and can withstand low temperatures, the most suitable storage temperature is about 274.65 K [23]. So, it can be stored at low temperatures. Hypobaric fumigation storage reduces the air pressure of the storage place through the hypobaric storage equipment to form a certain vacuum degree, then the environment is pre-cooled by refrigeration equipment to quickly reduce the heat brought by the fruit from the outside, so the hypobaric fumigation storage is a process of integration of hypobaric and vacuum pre-cooling. The equipment adopts continuous pumping hypobaric technology and can achieve "continuous pumping, continuous humidification, continuous ventilation" continuous operations. The basic principle is shown in Figure 1, litchi is placed in a closed container at a low temperature, and the internal gas is extracted by a vacuum pump so that a low absolute pressure is formed in the container. When the pressure is reached, the green harmless fumigation gas or liquid enters the vacuum chamber to regulate the physiological characteristics of litchi cells, reduce the respiratory intensity of litchi, inhibit the production of ethylene, improve the environmental adaptability of litchi after harvest, and can kill insects and sterilization, to prolong its storage period. In a vacuum negative pressure environment, fumigated gas or liquid is more permeable, can penetrate litchi tissue, regulate the physiological characteristics of litchi, and delay the aging of cell tissue. Moreover, the permeability of fumigation gas under vacuum negative pressure is much better than that under normal pressure.

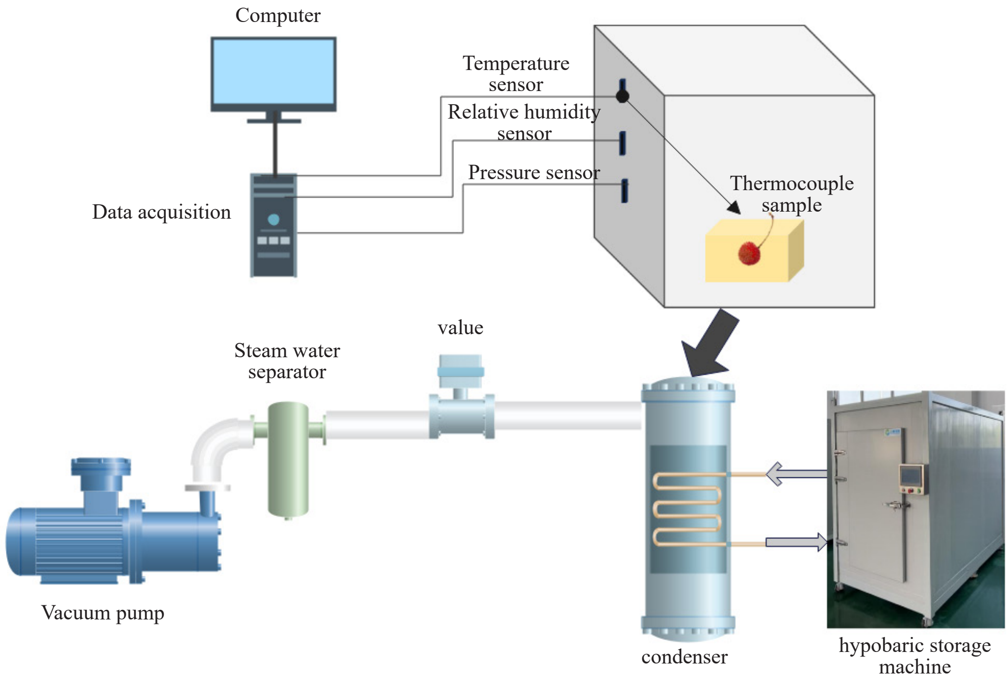

Figure 1. Principle of hypobaric fumigation

3. Experimental materials and methods

3.1 *Materials and instruments*

Ingredients: The fresh litchi were cleaned and divided into 4 groups of equal weight, 500 g each, and were fumigated under the humidification specific gravity of 0%, 2%, 3%, and 5%, respectively [24]. The above experiment was repeated for 3 times, and the average value was taken to study the changes of temperature and pressure in the vacuum chamber. The thermocouple probe was inserted into the center and surface of the litchi to measure the center temperature and surface temperature.

Equipment: i2000 electronic scale (Yalipo E-commerce Co., LTD., Suqian, China), accuracy is ± 0.01 g; Handheld refractometer; JYL2A double vacuum chamber vacuum storage experimental machine (Shanghai Kind-water Preservation Fresh TECH Co., Ltd).

3.2 *Measurement of weight loss rate*

The weight loss rate is calculated by measuring the weight with an electronic scale. The weight of the sample is measured once before and after hypobaric fumigation storage. The calculation formula is as follows:

$$\mu(\%) = \frac{m_1 - m_2}{m_1} \times 100\% \tag{1}$$

Where: μ is the weight loss rate; m_1 is the mass before storage, kg; m_2 is the mass after storage, kg.

3.3 *Measurement uncertainties*

The accuracy is based on experimental equipment and collecting methods. Propagation errors are also carefully considered in this work. The factors of propagation errors are invested and perfect recursive paths are found in practice [25]. The measurement uncertainties are reported in Table 1. The components in the table belong to the vacuum storage experimental machine.

$$\frac{\partial Q}{\partial \delta}=\frac{\delta}{A\Delta T} \tag{2}$$

$$\frac{\partial \lambda}{\partial \delta}=\frac{Q}{A\Delta T} \tag{3}$$

$$\frac{\partial \lambda}{\partial \Delta T}=-\frac{Q\delta}{A(\Delta T)^2} \tag{4}$$

$$\frac{\partial \lambda}{\partial A}=-\frac{Q\delta}{A^2\Delta T} \tag{5}$$

$$m\lambda=\pm\sqrt{\left(\frac{\partial \lambda}{\partial Q}\right)^2 m^2{}_Q+\left(\frac{\partial \lambda}{\partial \delta}\right)^2 m^2{}_\delta+\left(\frac{\partial \lambda}{\partial \Delta T}\right)^2 m^2{}_{\Delta T}+\left(\frac{\partial \lambda}{\partial A}\right) m^2{}_A} \tag{6}$$

where, Q is heat flow, W; m is error; λ is thermal conductivity, W/(m · K); δ is thickness, m; l is length, m; $m_Q = \pm\ 0.01\ Q$, $m_\delta = \pm\ 0.012\ \delta$, $\Delta T = 20$ K, $m_{\Delta T} = \pm\ 0.15$ K, $A = 2$, $m_A = \pm\ 2$, $l\ |ml| = \pm\ 0.04\ l$. Therefore, $m\lambda$ can be specified as:

$$m\lambda=\pm\sqrt{\frac{Q^2\delta^2}{l^4\times 4.0\times 10^6}+\frac{9Q^2\delta^2}{l^4\times 2.5\times 10^7}+\frac{9Q^2\delta^2}{l^4\times 6.4\times 10^7}+\frac{Q^2\delta^2}{l^6\times 2.5\times 10^5}} \tag{7}$$

The size of the radius of litchi selected in this work is about 12 mm. Since litchi is hypothesized to be a uniform sphere of the same radius, l is equal to δ is equal to the diameter of the litchi. According to the analysis of the propagation errors formula, $m\lambda$ is about ± 0.01326 W/(m·K), which meets the accuracy calculation requirements.

Table 1. Measurement uncertainty

Components	Type	Error
Thermocouple	PT-100	± 0.27 K
Thickness sensor	SL-2000	± 1.2%
Pressure sensor	DJYB-300C	± 0.5%
Measure power	Shunt resistor	± 1 Pa
Vernier caliper	MNT-150	± 0.02 mm

4. Experimental results and discussion

4.1 *Simulating temperature changes in litchi*

ANSYS FLUENT was used to simulate the internal temperature distribution of vacuum pre-cooling during hypobaric, and the pre-cooling time was set at 0, 100, 200 and 300 s [15], respectively. The following is a screenshot of the internal temperature cloud image of litchi during hypobaric fumigation. It can be seen from Figure 2 that the surface temperature change of litchi is greater than the center temperature change. When the pre-cooling time is 0 s, there is no heat exchange between the surface and the center of litchi, and the initial temperature is about 300 K. When the hypobaric storage machine is started, the vacuum pump begins to work so that the pressure in the vacuum chamber drops sharply, and the heat absorbed by water vapor evaporation takes away the heat of litchi so that the surface temperature of litchi begins to drop first. With the increase of the pre-cooling time, the center temperature of litchi also begins to slow down. When the pre-cooling time is 300 s, the surface temperature and center temperature of litchi are stable at about 283 K and 288 K, which is not much different from the results obtained in the experiment.

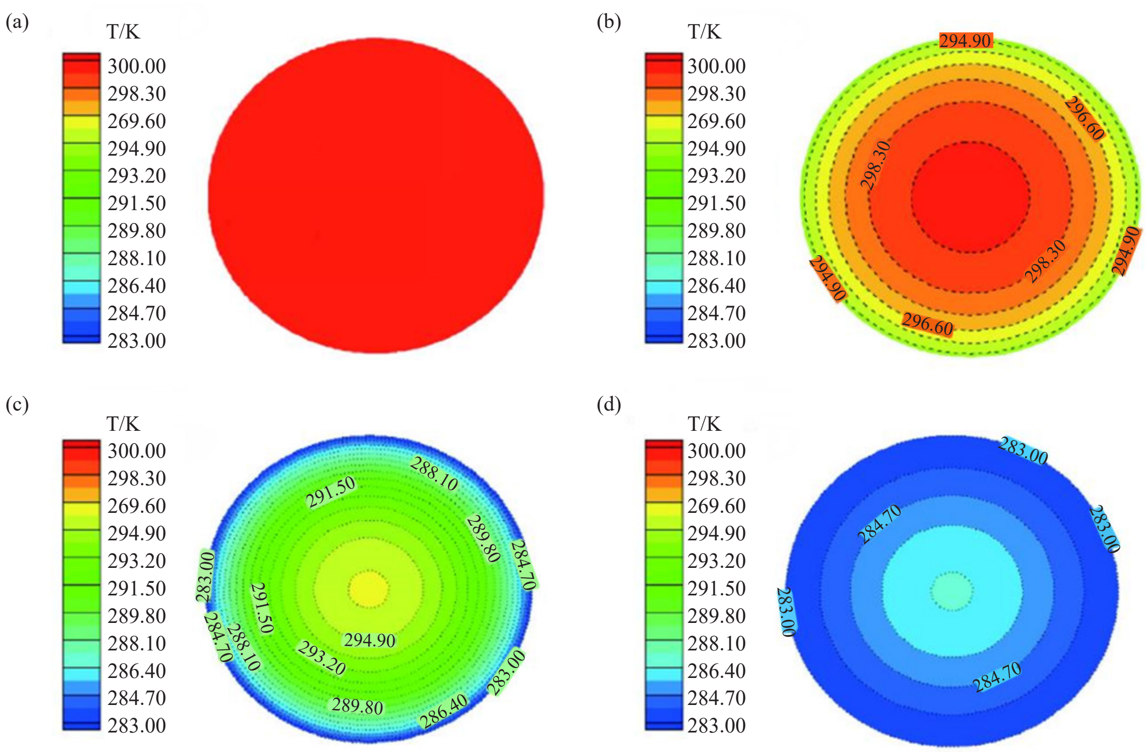

Figure 2. Temperature profiles inside litchi after hypobaric storage

4.2 *Comparison of vacuum chamber pressure simulation and experimental values*

Figure 3 shows the comparison between the experimental value and the simulated value of vacuum chamber pressure. It can be seen from the Figure that the experimental value and the simulated value have the same change trend. After the vacuum pump is started, the vacuum chamber pressure drops sharply, but there is a slight difference between the experimental value and the simulated value in the first 100 s, and the latter is basically the same. The other conditions are in an ideal state, so the pumping efficiency is high and the pressure drop is fast; During the experiment, the power of the vacuum pump is not constant, it is low at first, and then gradually becomes constant. After the vacuum pre-cooling during hypobaric fumigation, the experimental values agree with the simulated values, with an error of only 2.6%.

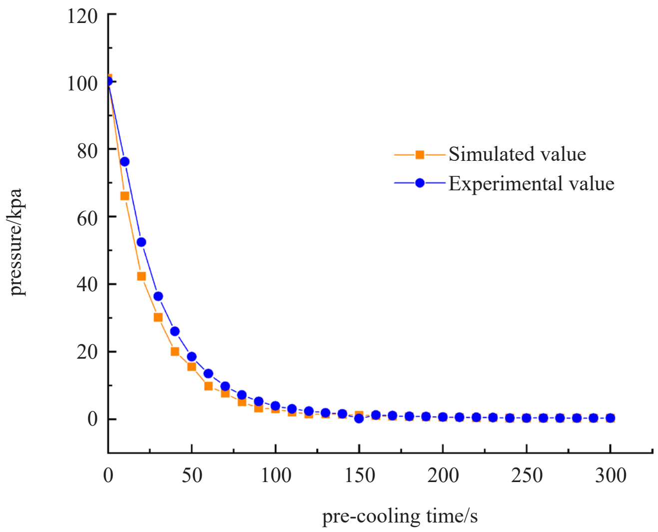

Figure 3. Comparison of experimental and simulated pressure values

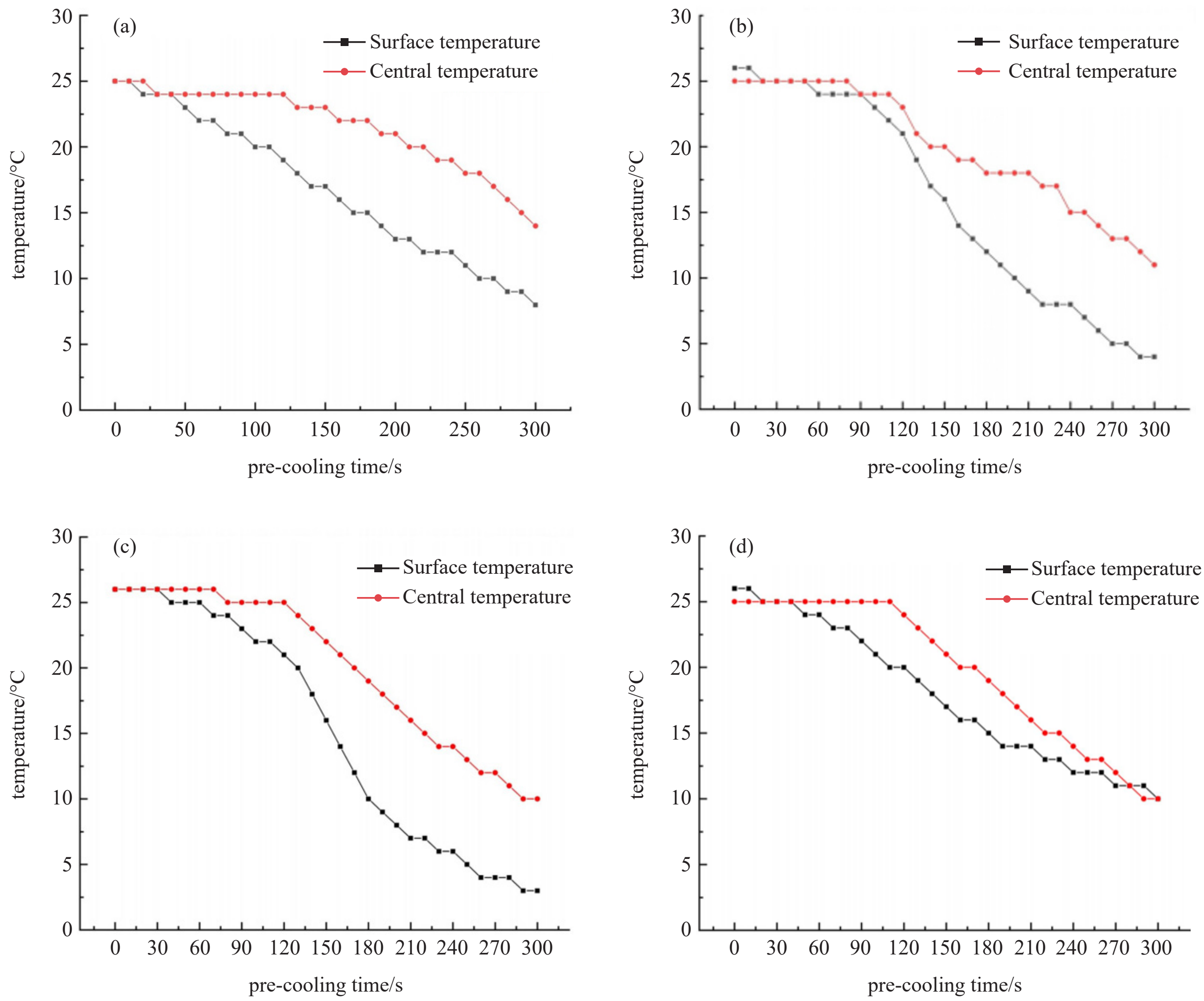

Figure 4. Variation of center and surface temperature (a-0%; b-2%; c-3%; d-5%)

4.3 *Effect of different humidification gravity on temperature*

Figure 4 (a-d) show the changes of the center temperature and surface temperature under the four humidification specific gravity of 0%, 2%, 3%, and 5%, respectively. It can be seen from the figure that the center temperature of litchi changes slowly, while the surface temperature changes rapidly. In general, there is the same trend of change, and both decrease with the increase of pre-cooling time. The difference between the surface temperature and the center temperature is most obvious when the specific humidification is 2% and 3%. The reason for this phenomenon is that in the process of pre-cooling, with the reduction of pressure, the water vapor on the surface of the litchi evaporates first and takes away the heat first. With the increase of pre-cooling time, the internal water vapor gradually evaporates. However, when the humidification proportion is 5%, the humidification proportion is too large, and the surface water of litchi is too much, resulting in the evaporation and heat absorption becoming slow, so the difference between the central temperature change and the surface temperature change is not so obvious.

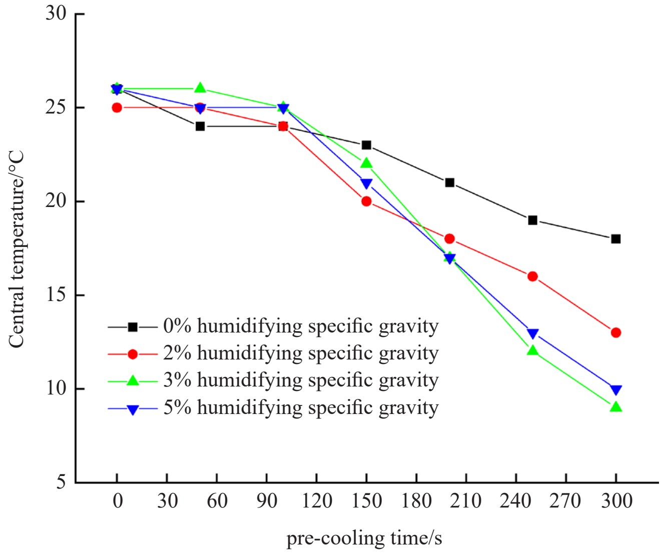

Figure 5. Changes of center temperature

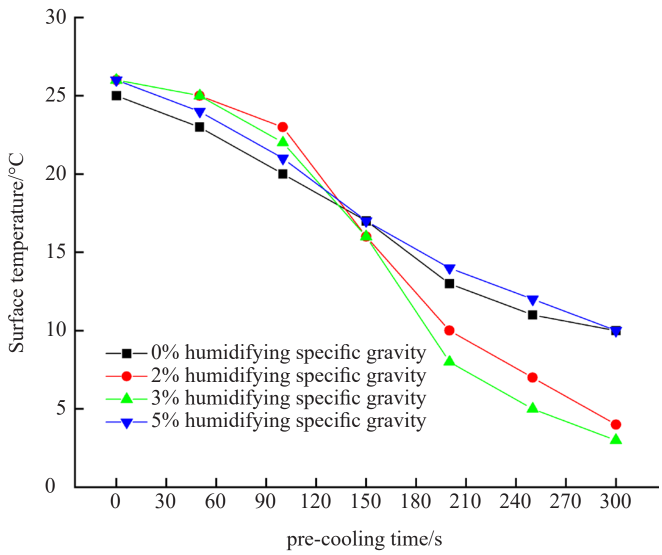

Figure 6. Changes of surface temperature

4.4 *Temperature drop of litchi center and surface temperatures*

As can be seen from Figures 5 and 6, there are obvious changes before and after 100 s. Before this, both the central temperature and the surface temperature decrease slowly under different humidification specific gravity, and after this, the central temperature and the surface temperature decrease rapidly. Among them, the performance is most obvious when the humidification proportion is 3%, so it proves that the humidification proportion is not the higher the better, but to choose an appropriate proportion to achieve an optimal balance state, so that it is more conducive to cooling. It can be seen in the Figure that when the humidification proportion is 3%, the center temperature and surface temperature drop to the lowest, the best effect.

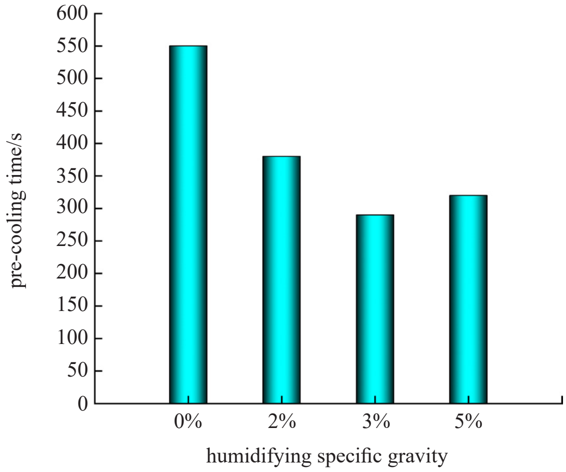

Figure 7. Effect of surface final temperature of 277.15 K on pre-cooling time

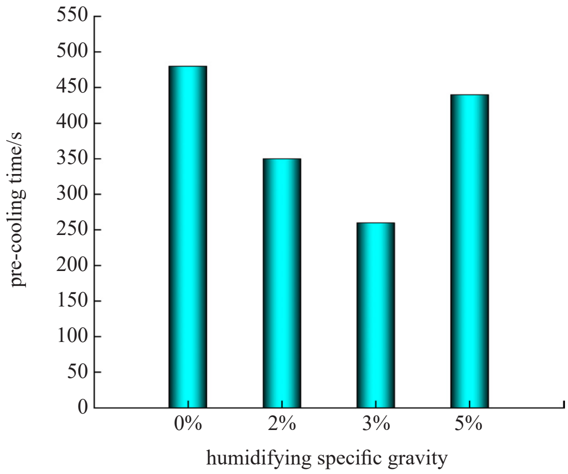

Figure 8. Effect of central final temperature of 283.15 K on pre-cooling time

4.5 *Effect of the same pre-cooling final temperature on pre-cooling time*

As can be seen in Figure 7 and Figure 8, the time required to pre-cool to the same temperature varies for different humidification gravities, with surface temperatures pre-cooled to 277.15 K and center temperatures pre-cooled to 283.15 K. The time required to pre-cool to the same temperature varies for different humidification gravities. Increasing the specific gravity of humidification can shorten the pre-cooling time, so that the surface and center of the litchi cool down quickly, inhibit its respiration, and prolong the freshness period of the litchi. The experimental results show that when the specific gravity of humidification is 3%, the pre-cooling time of litchi is the shortest for the temperature of the surface and center of the litchi, which is 260 s and 290 s respectively.

4.6 *Effect of humidification specific gravity on weight loss of litchi*

Figure 9 shows the influence of different humidification specific gravity on the weight loss before and after pre-cooling. Without humidification, the weight loss is 4.26%, and the weight loss is the largest; when the humidification specific gravity is 5%, the weight loss is -1.2%, indicating that the mass before and after precooling does not decrease but increases. The reason for this may be that the humidification specific gravity is too large, and water vapor migrates to the surface of the litchi, which increases the surface moisture. The formation of boundary layer, evaporation heat absorption is not sufficient, so the comprehensive surface and center temperature changes, when the humidification is 3%, the best effect.

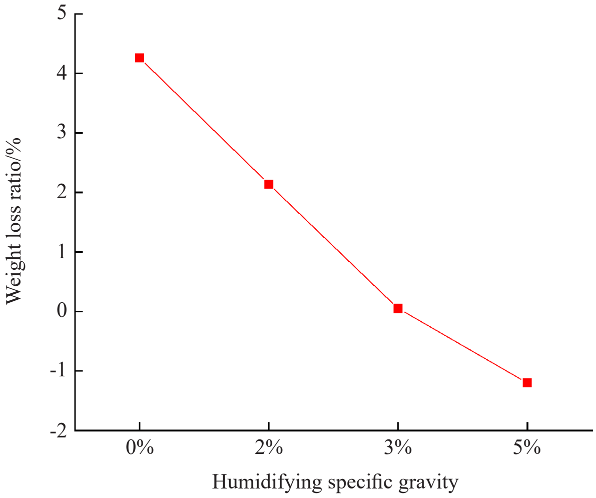

Figure 9. Effect of different humidification specific gravity on weight loss

4.7 *Error analysis*

This experiment and simulation have some errors, the main reasons are: 1) the actual situation is that litchi is not a uniform sphere, and in the simulation process, it is regarded as a uniform sphere. Therefore, the simulation results for pressure are slightly different from the actual results, but the error is only 2.6%; 2) When using thermocouples to measure the temperature, the probe needs to be inserted into the center of the litchi and the epidermis, and the density and moisture of the various parts of the litchi in the experiment varied slightly, while the simulations were all carried out in an ideal state, so there were errors in the results; 3) The pressure drop in the vacuum chamber has a direct relationship with the vacuum pump, the power of the vacuum pump is not constant, and there is an error in the measured pressure each time it is pre-cooled.

5. Conclusion

Through the hypobaric storage numerical simulation of litchi, the hypobaric storage model of spherical fruits and vegetables was established, and the effect of different humidification weights on the surface and center temperatures of litchi was analyzed during the hypobaric fumigation process. The following conclusions were drawn:

(1) In the hypobaric storage heat and mass transfer simulation, the power of the vacuum pump has been kept constant, while the experimental vacuum pump rated power of 1,300 W. During the initial operation period, the vacuum pump's power was low, and it then gradually converged to a constant. At the beginning, the pressure simulation value was slightly lower than the experimental value, but finally, the two values basically coincided with an experimental error of only 2.6%.

(2) Among the humidification specific gravity of 0%, 2%, 3%, and 5%, when the humidification specific gravity is 3%, the surface temperature of litchi reaches 277.15 K and the center temperature reaches 283.15 K, representing the lowest temperature among all the groups. Thus, the humidification specific gravity of 3% is more effective in cooling litchi.

(3) In the litchi hypobaric storage experiments, with a rapid decline in the pressure of the vacuum chamber, litchi water vapor evaporation from the outside to the inside. As a result, the surface temperature is always lower than the center temperature.

(4) Setting the final surface pre-cooling temperature to 277.15 K and the final center temperature to 283.15 K, in the humidification specific gravity of 0%, 2%, 3%, and 5%, when the humidification specific gravity is 3%, the pre-cooling time for the surface temperature of 277.15 K is 260 s, and for the center temperature of 283.15 K is 290 s, and the required time is the shortest.

(5) Litchi was weighed before and after pre-cooling, and theweight loss was minimized at a humidification-specific gravity of 3%, with a weight loss of only 0.05%.

Ethical statement

Ethical permission, to conduct a human sensory study, is not a requirement of our institution. Our research institution does not harm volunteers recruited for sensory experiments. The food we purchase is all qualified food from the regular channels of market inspection and quarantine.

Data availability

The datasets supporting the conclusions of this article are included within the article, and the sequencing data correspond with Figures. It will be made available upon reasonable academic request within the limitations of informed consent by the corresponding author upon acceptance.

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Conflict of interest

The authors declare no competing interests.

References

[1] Lin L, Luo X, Yu H, Wang Q, Zhang Z, Li K. The effect of postharvest water migration on metabolism of cassava

root by hypobaric storage. *Innovative Food Science & Emerging Technologies*. 2024; 93: 103609.
[2] James A, Yao T, Ma G, Gu Z, Wang Y. Effect of hypobaric storage on Northland blueberry bioactive compounds and antioxidant capacity. *Scientia Horticulturae*. 2022; 291: 110609.
[3] Chen H, Ling J, Wu F, Zhang L, Sun Z, Yang H. Effect of hypobaric storage on flesh lignification, active oxygen metabolism and related enzyme activities in bamboo shoots. *LWT-Food Science and Technology*. 2013; 51(1): 190-195.
[4] Zheng XZ. Research and application of hypobaric storage technology in agriculture and food industry in China. *Asian Agricultural Research*. 2018; 10(6): 12.
[5] Hashmi MS, East AR, Palmer JS, Heyes JA. Pre-storage hypobaric treatments delay fungal decay of strawberries. *Postharvest Biology and Technology*. 2013; 77: 75-79.
[6] Li J, Bao X, Xu Y, Zhang M, Cai Q, Li L, et al. Hypobaric storage reduced core browning of Yali pear fruits. *Scientia Horticulturae*. 2017; 225: 547-552.
[7] Davenport TL, Burg SP, White TL. Optimal low-pressure conditions for long-term storage of fresh commodities kill Caribbean fruit fly eggs and larvae. *HortTechnology*. 2006; 16(1): 98-104.
[8] Burg SP, Davenport TL. Heat transfer, mass transport and horticultural commodity water loss during hypobaric storage. *Scientia Horticulturae*. 2017; 225: 561-566.
[9] Sun DW, Brosnan T. Extension of the vase life of cut daffodil flowers by rapid vacuum cooling. *International Journal of Refrigeration*. 1999; 22(6): 472-478.
[10] Brosnan T, Sun DW. Influence of modulated vacuum cooling on the cooling rate, mass loss and vase life of cut lily flowers. *Biosystems Engineering*. 2003; 86(1): 45-49.
[11] Mutlu Ozturk H, Ozturk H, Kocar G. Comparison of vacuum cooling with conventional cooling for purslane. *International Journal of Food Engineering*. 2011; 7(6). Available from: https://doi.org/10.2202/1556-3758.2442.
[12] He SY, Zhang GC, Yu YQ, Li RG, Yang QR. Effects of vacuum cooling on the enzymatic antioxidant system of cherry and inhibition of surface-borne pathogens. *International Journal of Refrigeration*. 2013; 36(8): 2387-2394.
[13] Alibas I, Koksal N. Forced-air, vacuum, and hydro precooling of cauliflower (*Brassica oleracea* L. var. botrytis cv. Freemont): part I. Determination of precooling parameters. *Food Science and Technology*. 2014; 34: 730-737.
[14] Hashmi MS, East AR, Palmer JS, Heyes JA. Hypobaric treatments of strawberries: A step towards commercial application. *Scientia Horticulturae*. 2016; 198: 407-413.
[15] Zhu Z, Li Y, Sun DW, Wang HW. Developments of mathematical models for simulating vacuum cooling processes for food products-a review. *Critical Reviews in Food Science and Nutrition*. 2019; 59(5): 715-727.
[16] Huan C, Li H, Jiang Z, Shen S, Zheng X. Effect of hypobaric treatment on off-flavour development and energy metabolism in 'Bruno' kiwifruit. *LWT-Food Science and Technology*. 2021: 136: 110349.
[17] Brailovsky I, Babchin A, Frankel M, Sivashinsky G. Fingering instability in water-oil displacement. *Transport in Porous Media*. 2006; 63: 363-380.
[18] Sun DW, Hu Z. CFD simulation of coupled heat and mass transfer through porous foods during vacuum cooling process. *International Journal of Refrigeration*. 2003; 26(1): 19-27.
[19] Wang L, Sun DW. Modelling vacuum cooling process of cooked meat-part 2: mass and heat transfer of cooked meat under vacuum pressure. *International Journal of Refrigeration*. 2002; 25(7): 862-871.
[20] Wang LJ, Sun DW. Numerical analysis of the three-dimensional mass and heat transfer with inner moisture evaporation in porous cooked meat joints during vacuum cooling. *Transactions of the ASAE*. 2003; 46(1): 107.
[21] Wang N, Kan A, Huang Z, Lu J. CFD simulation of heat and mass transfer through cylindrical Zizania latifolia during vacuum cooling. *Heat and Mass Transfer*. 2020; 56: 627-637.
[22] Wang J, You Y, Chen W, Xu Q, Wang J, Liu Y, et al. Optimal hypobaric treatment delays ripening of honey peach fruit via increasing endogenous energy status and enhancing antioxidant defence systems during storage. *Postharvest Biology and Technology*. 2015; 101: 1-9.
[23] Zhou J, Wu J, Liu H, Lin X, Cheng L, Li C, et al. Low voltage electrostatic field combined with ice-temperature to improve the quality of litchi during storage. *Food Research International*. 2024; 196: 115068.
[24] Hashmi MS, East AR, Palmer JS, Heyes JA. Hypobaric treatments of strawberries: A step towards commercial application. *Scientia Horticulturae*. 2016; 198: 407-413.
[25] Kan A, Zhang Q, Chen Z, Zhang J, Wang K, Cao D. Novel prediction of thermal conductivities for nano-aerogel and its composites as vacuum insulation panel core. *International Journal of Thermal Sciences*. 2023; 189: 108277.